CROSSTALK SUPPRESSION TECHNIQUES FOR MULTI-CHANNEL REGENERATION BASED ON FIBER OPTIC PARAMETRIC AMPLIFIER

NOR ZAIDATUN NADRAH BT IBRAHIM

A thesis submitted in partial
fulfillment of the requirement for the award of the
Degree of Master of Electrical Engineering

Faculty of Electrical and Electronic Engineering
Universiti Tun Hussein Onn Malaysia

JANUARY, 2015

A special dedication to:

"My father, my mother"

IBRAHIM BIN DIN & TIJAH BT AHMAD

"My beloved siblings"

NOR LAILATUN ZAHARAH BT IBRAHIM

NUR FAEZAHTUN BT IBRAHIM

And

All my beloved friends,

Thank you for giving me support and chance to be what I can be.
Finally, this thesis is dedicated to all those who believe in the richness of learning.

ACKNOWLEDGEMENT

Praise be to Allah the lord of the worlds and universe, with his consent I was able to complete this study.

I would like to express my appreciation to Dr, Nor Shahida bt Mohd Shah, my project supervisor for her insightful comments, encouragement and advice which helped greatly in improving the quality of this project. Without her continued support and interest, this thesis would not have been the same as presented here.

I also would like to extend my sincere appreciation to lectures and staff of UTHM who have provided assistance at various occasions. To my colleagues for the precious help, sacrifices, stimulation and encouragement during the years of my studies thanks to shared your happiness and constraint.

I would like to dedicate this work to my beloved daddy Mr. Ibrahim Bin Din and my mum, Mrs.Tijah Bt Ahmad, who has strived hard to ensure that I have complete this project on the time. Thanks for being my backbone all the time.

Last but not least, thanks all those who have generously published their works online. Their works have been the most useful reference source for this project.

THANK YOU

ABSTRACT

Optical transmission system is the best choice to transmit high capacity information over long distances. The progressive development in optical transmission technologies allows the growth of transmission speed and capacity.2R or 3R regeneration can refine the degraded signal and improve transmission performance. 2R stands for reamplifying and reshaping the signal, and 3R adds retiming of the signal. Conventionally, electrical repeaters are used for the regenerations. In this regeneration system, the signal is converted from optical to electrical, regenerated electrically and finally converted back to an optical. Besides the electrical repeater, all optical regenerator is an alternative to regenerate optical signal without the need of optical electrical optical signal conversions. All optical signal regeneration has been recognized as a potential enabler of future transparent long haul high bit rate systems. All optical regeneration is easily applicable to various modulations formats signals and can work ultrafast. Since fiber based all optical regeneration was introduced two decades ago, many excellent techniques to regenerate signals have been proposed was introduced in order to reduce nonlinear effect within the channel, two techniques approaches being polarization interleaving and polarization multiplexing. The purpose of the signal regeneration is therefore to remove these distortions and to restore the characteristics of the optical signal to a suitable level so that a high overall transmission quality is maintained. As a result, the improvement of Q factor of each regenerated channel can be more improved for each techniques. In this result, a WDM system with polarization based system is analyzed in order to mitigate the nonlinear effects within the fiber channel. Hence, the performance can be further improved by using concept of polarization modulation in the transmitter section WDM system.

ABSTRAK

Sistem penghantaran optik merupakan sistem yang terbaik untuk menghantar data kapasiti yang tinggi bagi jarak jauh.Pembangunan yang progresif dalam sistem penghantaran optik membolehkan kelajuan penghantaran dan kapasiti. 2R atau 3R merupakan pertumbuhan semula bagi menapis isyarat yang disorot dan meningkatkan prestasi penghantaran.2R bermaksud menguatkan dan membentuk semula isyarat dan 3R penambahan pengaturan masa. Lazimnya, elektrik adalah digunakan untuk penjanaan semula isyarat. Dalam sistem penjanaan semula, isyarat akan ditukarkan dari optik ke elektrik, elektrik akan dijana semula dan akhirnya ditukarkan kembali kepada optik. Selain pengulangan elektrik, semua penjana optik merupakan alternatif untuk menjana semula isyarat optik tanpa memerlukan penukaran isyarat elektrik optik. Semua penjana optik telah dikenali sebagai pemboleh potensi jarak jauh untuk sistem kadar bit yang tinggi bagi masa hadapan. Semua penjana optik adalah mudah diguna pakai untuk pelbagai isyarat format modulasi dan ia boleh beroperasi dengan kelajuan tinggi.Semenjak semua penjana optik diperkenalkan dua dekad yang lalu, pelbagai teknik di perkenalkan untuk menjana semula isyarat bagi mengurangkan kesan tidak linear dalam saluran, terdapat dua teknik yang digunakan bagi mengurangkan kesan tidak linear iaitu pengutuban sisipan saluran dan pengutuban banyak unsur saluran..Oleh itu tujuan penjanaan semula isyarat ini adalah untuk menghapuskan herotan dan mengembalikan ciri-ciri isyarat optik ke tahap yang sesuai supaya keseluruhan kualiti penghantaran yang tinggi dapat dikekalkan. Kesannya peningkatan faktor kualiti bagi setiap saluran menjadi lebih baik untuk setiap teknik. Didalam keputusan ini , sistem WDM menggunakan pengutuban dianalisi bagi mengurangkan kesan tidak linear dalam saluran.Oleh itu prestasi boleh dipertingkatkan lagi dengan menggunakan konsep pengutuban modulasi dalam sistem WDM dibahagian pemancar.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

CD	Chromatic dispersion
CW	Continuous wave
DMUX	De-multiplexer
DPSK	Differential phase shift keying
DSF	Dispersion shifted fiber
DWDM	Dense wavelength division multiplexed
EDFA	Erbium-doped fiber amplifier
FOPA	Fiber optical parametric amplifier
FRA	Fiber Raman amplifier
FWM	Four-wave mixing
HNLF	Highly Nonlinear Fiber
NRZ	Non Return Zero
PMD	Polarization mode dispersion
PRBS	Pseudo random binary sequence
SMF	Single Mode Fiber
SOP	State of Polarization
SPM	Self Phase Modulation
WDM	Wavelength Division Multiplexing
XPM	Cross Phase Modulation

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Project Background

This project focuses on the investigation of crosstalk suppression techniques for multi-channel regeneration based on fibre optic parametric amplifier (FOPA). In this study we imply three crosstalk suppression methods including polarization multiplexing, interleaving and bidirectional transmission based dual-wavelength regeneration system. All optical regeneration, especially re-amplifying, reshaping and retiming is capable of improving the quality of degraded signals, resulting from fibre loss, dispersion, nonlinearity and amplified spontaneous emission (ASE) noise. The reshaping function can be realized using nonlinear effects, such as self-phase modulation (SPM) [1-3], cross phase modulation (XPM) [4], cross gain modulation (XGM) [5], four wave mixing (FWM) [6], saturated absorption [7] and nonlinear interferometer [8]. In wavelength-division-multiplexing (WDM) systems, multi channel regenerators are desired, instead of a regenerator per channel, to reduce cost [9]. However, the main issue is nonlinear the inter-channel crosstalk. In SPM-based 2R regeneration, polarization multiplexing [10], bidirectional transmission [11] and dispersion management [12] have been used to suppress the inter-channel crosstalk. By using polarization multiplexing and bidirectional transmission, four wavelength 3R regeneration based on a fibre optical parametric amplifier (FOPA) configuration will be demonstrated [13]. Furthermore the FWM-based dual-wavelength regeneration was also realized by using the time-interleaving technique [14,15]. In fact, compared with the SPM-based regeneration, the FWM-based regeneration has some unique advantages in wavelength conversion and 3R regeneration. FWM based regenerations can be classified as data-pump and high order cases [16-20], and the corresponding idler or high-order FWM products are regarded as the regenerated signals. Both schemes can improve the extinction radio (ER), when the input power is low and further suppress the amplitude fluctuations when the input power is high.

1.2 Problem Statement

Optical transmission system is the best choice to transmit high capacity information over long distance. The rapid progress of optical communication to full high data rates demands has been made possible by wavelength division multiplexing (WDM) technology. In WDM system, a number of channels at different wavelengths are simultaneously transmitted through one fibre. However, most of all optical regenerators studied only concern single channel operation. Thus, for the use in WDM systems, the number of regenerators required is proportional to the number of channel. For the multi-channel regeneration, interchannel nonlinear crosstalks in the nonlinear medium have to be avoided while efficient nonlinear effect is needed in the regeneration process. The nonlinear properties can be obtained by injecting sufficiently high light intensities material, such as fibre, semiconductor and silicon. Various types of nonlinear effects can, be used for fibre based signal regeneration such as FWM. High local dispersion can suppress interchannel FWM. In response to this situation, this proposed investigation of crosstalk suppression technique.

1.3 Aim

The investigation and implementation of crosstalk suppression technique for multichannel regeneration based on FOPA is the aims of this research study in order to improve performance between signal channels.

1.4 Objectives

- To design system polarization interleaving channels
- To design system polarization multiplexing channels
- To design system without polarization

- Evaluate the each performances of the crosstalk techniques by considering the following eye diagrams and optical spectra

1.5 Scope Of Project

The scopes of this project study is to investigate the performance of polarization interleaving and polarization multiplexing of crosstalk suppression technique for multichannel.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This part describes the theoretical background of crosstalk suppression technique for multichannel based on FOPA and the observation by reviewing the previous project that related to this project study.

2.2 Fiber Optic Communication

Fiber optic communication system is just like every other communication system. An optical communication system is shown in Figure 2.1. The main parts of system are transmitter consisting of light source, a cable as a medium for protection from environmental effects and a receiver consisting of photo detector, amplifiers, regenerator.

The information source could be any physical quantity like sound, video, dat. This information is sent to electrical transmitter. Transmitter is usually a transducer, which converts a message signal into electrical signal. Usually we convert this electrical signal into digital form using ADC, because in fiber optics we are dealing with light and difficult to deal with analogue communication. Digital signal is sent through the fiber because it’s easy to deal with digital signal.

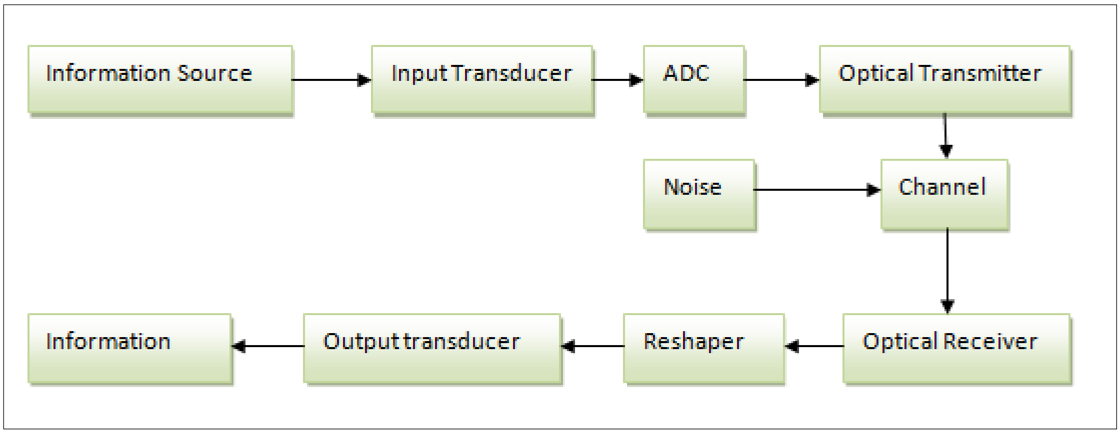

Figure 2.1: Optical Communication System

The Shannon-Hartley theorem states that, regardless of specific technology, the information carrying capacity is proportional to channel bandwidth, the range of frequencies within which the signals can be transmitted without substantial attenuation or mathematically:

$$C = W.\log_2(1 + \frac{S}{N}) \quad (2.1)$$

Where W is the bandwidth of a signal being transmitted over a noisy communications channel, S/N is the signal to noise ratio and C is the channel capacity, measured in bits per second. It is the frequency of the signal carrier that limits the channel bandwidth. The higher the carrier's frequency, the greater the channel bandwidth and the higher the information carrying capacity of the system. A copper wire can carry 1 MHz signal. A coax can carry a 100 MHz signal. A fiber optic transmission link can carry a 1000THz signal. Now, if bandwidth is say 10 % of the carrier, the bandwidth increases appreciatorily by from cooper to fiber optics. Consider these transmission media in terms of their capacity to carry, simultaneously, a specific number of one-way voice channels. A single coaxial cable can carry up to 13000 channels, a microwave terrestrial link up to 20000 channels and a satellite link up to 100000 channels. However, one ordinary fiber optic communication link, can carry 300000 two way voice channels simultaneously, which explain why fiber optic communication systems form the backbone of modern telecommunications and will most certainly shape its future. Table 2.0 summarizes the bandwidth relations:

Table 2.1: Summary of bandwidth and channels

	Carrier Frequency (Hz)	Bandwidth (Hz)	Channels
Copper wire	10^6	10^5	-
Coax	10^8	10^7	13000
Microwaves	10^{10}	10^9	20000
Fiber optic	10^{15}	10^{14}	300000

2.3 Basic Concepts of Optical Amplifiers

Optical amplifiers, which are the key enabling technology for WDM systems, can amplify multiple wavelength in the optical domain in the optical domain without requiring conversion to the electrical domain. Ever since EDFAs were successfully implemented as optical amplifiers, a lot of research has been done not only on the EDFA itself, but also on other types of optical amplifiers which use different material and working mechanisms.

2.4 Principle of Fibre Optic Parametric Amplifier (FOPA)

The fundamental principles of FOPAs have been known for more than twenty years, it is only recently that it has become possible to implement these in a practical way. The characteristics of FOPA are the high power, single-wavelength pump laser and a specifically tailored highly nonlinear, low dispersion optical fibre and FOPA is a new kind of amplifier which relies on the nonlinear process four-wave mixing. The parametric amplification occurs when FWM takes effect between a strong pump beam at ω_p and a weak signal beam ω_s propagating in a highly nonlinear fiber (HNLF). When the two beams are co-propagating in the fiber their frequencies are beating with each other due to Kerr effect. As a result the refractive index of the fiber is modulate with the frequency $\omega_p - \omega_s$. The modulated refractive index acts as a phase modulator for the pump beam and creates sidebands at $\omega_p - (\omega_p - \omega_s) = \omega_s$ and $\omega_p + (\omega_p - \omega_s) = \omega_{i.}$ Therefore the signal is amplified due to parametric gain, while a new wave, generally called idler, is generated simultaneously. FOPAs have important characteristics which make them have the potential to be used for a variety of applications. These properties are listed below:

- Large gain and bandwidth

  By using one or two pumps, FOPAs can provide relatively larger gain and bandwidth compared to EDFA .

- Arbitrary centre wavelength

  The centre wavelength , λ_c of the gain region in FOPAs can be any arbitrary wavelength. However it should be noted that the zero dispersion wavelength (ZDW) of the fiber should be close to λ_c.

- Wavelength conversion

  Besides amplifying the input signal, a new wavelength component is generated by the FOPA. This feature can be used for creating new wavelengths for wavelength routing in optical networks. The signal to idler conversion efficiency can be high as the signal gain, therefore leading to large conversion efficiencies which cannot be obtained with other conversion techniques. Dual pump FOPAs can produce multiple idlers at the same time.

- Spectral inversion

  In FOPAs the idler spectrum is symmetric to the signal spectrum with respect to the central frequency. This feature can be used for dispersion compensation in communication systems.

- Phase conjugation

  The idler's phase is opposite to that of the original signal. Some nonlinear effects such as cross phase modulation which affect the phase of the waves can be counteracted using this idler property.

- High speed optical signal processing

  The ultrafast nature of the nonlinear response of FOPAs is useful for many applications. Generally high speed modulation of the pump will result in modulation of the signal and idler which can be used for applications such as pulse generations, regeneration of signal pulses and all optical sampling.

- Low noise figure

  FOPAs can theoretically have a noise figure of 0 dB while operating in phase sensitive mode.

- Unidirectional gain

  Unlike EDFA, in FOPA only the signal waves which propagate the pump get amplified. Therefore, it doesn't provide gain for the reflections from the end of the amplifier.

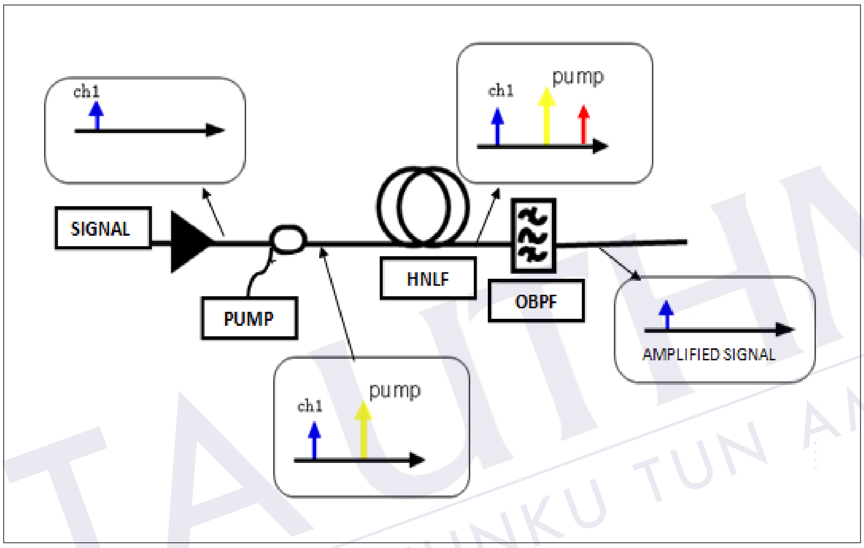

Figure 2.2 : Single pump FOPA configuration. HNLF: High Nonlinear Fiber; OBPF: Optical Band Pass filter

The FOPA is unique in many ways when comparing with other amplifiers, example having a gain spectrum almost entirely dictated by the dispersion properties of the fibre and the possibility of reaching a quantum limited noise figure of 0dB. It provides unidirectional and single-polarization amplification and can have high pump-to-signal conversion efficiency as well as very high gain [21].Since FOPAs react almost instantaneously, they have several potential applications besides amplification including wavelength conversion [22], tunable filter [23], tunable delays [24], tunable lasers [25], pulse generation [26] and signal regeneration [27].

2.5 Multi-Channel Regeneration

In multi channel system, a signal channel suffers from FWM, which generates various combinations of different channel frequencies and cause crosstalk degradation [28].The rapid progress of optical communication to full fill the high data rates demand has been made possible by wavelength division multiplexing (WDM) technology. In WDM system, a number of channels at different wavelengths are simultaneously transmitted through one fibre.

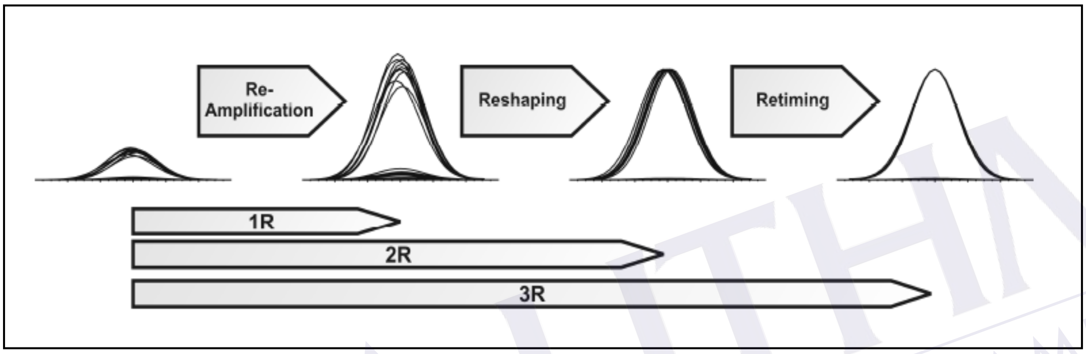

Figure 2.3 : Signal regenerator scheme illustrating the re-amplification, reshaping and retiming operations on a input signal. Note that the order of reshaping and retiming can be independently exchanged for 3R regeneration schemes.

For the multi-channel regeneration, interchannel nonlinear crosstalks in the nonlinear medium have to be avoided while efficient nonlinear effect is needed in the regeneration process. Some technique for fibre based multi-channel regeneration have been proposed. Most of the studies use dispersion management to suppress interchannel crosstalk [29]. High local dispersion can suppress interchannel FWM and XPM. In reference of [30], polarization orthogonalization between adjacent channels is used in addition to fibre dispersion management for suppression of the XPM effect. For references [31] applies the periodic group delay devices as the dispersion compensators to ensure fast bit walk off between different channels, and the suppress the interchannel XPM as well as FWM. Other study proposed bidirectional configuration to avoid interchannel crosstalk, but the number of channels is limited [32]. Interchannel crosstalk mitigation by properly time-interleaved channels is another method introduced in references [33]. Multi-channel regeneration is conceivable because their short gain response time in the order of 100 ps to 1 ps leads to negligible patterning effects and spatial isolation of quantum dots leads to spectrally localized effects.

Other than fiber nonlinearity, nonlinearity in semiconductor optical amplifiers (SOAs) is also available for all regeneration. However, only a few SOA based regeneration have been proposed for multi-channel regeneration because of high interchannel cross gain modulation (XGM) interaction [34]. Quantum dot SOAs have been studied to handle multiple WDM channels [35,36]. Multi-channel regeneration is conceivable because their short gain response time (in the order of 100ps to 1ps) leads to negligible patterning effects, and spatial isolation of quantum dots leads to spectrally localized effects. However, very little experimental demonstration has been reported to date in support of the encouraging numerical predictions as quantum dot devices with very low XGM have not been implemented yet. Interchannel crosstalk mitigation by time interleaving channels has also been proposed in SOA based regenerator.

2.6 Concept of Polarization

Polarization is a property of electromagnetic radiation describing the shape and the orientation of the electric field vector as a function of time, at a given point of the space.

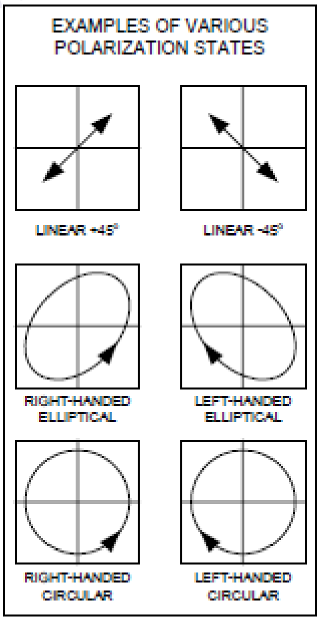

Figure 2.4: Example of different polarization states, which depend upon relative magnitude and phase between the two principle polarization

REFERENCES

[1] L. Provost, C.Finot, P.Petropoulos, K.Mukasa, D.J.Richardson, *Optics Express* 15(2007)5100

[2] M.Rochette, L.Fu, V.Ta'eed, D.J.Moss, B.J.Eggleton, *Journal of Selected Topics in Quantum Electronics* 12(2006)736.

[3] P.Mamyshev, “All-optical data regeneration based on self-phase modulation effect”, Optical Communication, 1998, in *24th European Conference on*, IEEE 1998.

[4] W.Wang, H.N.Poulsen, L.Rau,H.F. Chou,J.E.Bowers, D.J.Blumenthal, *Journal of Lightwave Technology* 23(2005)1105.

[5] G.Contestabile, R.Proietti, N.Calabretta, E.Ciaramella, *Journal of Lightwave Technology* 25(2007)915.

[6] E.Ciaramella, F.Curti, S.Trillo, *IEEE Photonics Technology Letters* (2001)142.

[7] H.T.Nguyen, C.Fortier, J.Fatome, G.Aubin, J.L.Oudar, *Journal of Lightwave Technology* 29(2011)1319.

[8] A.G.Striegler, M.Meissner, K.Cvecek, K.Sponsel, G.Leuchs, B.Schmauss, *IEEE Photonics Technology Letters* 17(2005)639.

[9] E. Ciaramella, *Journal of Lightwave Technology* 30(2012)572

[10] A.L.Yi, L.S.Yan, B.Luo, W.Pan, J.Ye, J.Leuthold, *Optics Express* 18(2010)7150

[11] F.Parmigiani, L.Provost, P.Petropoulos, D.J.Richardson, W.Freude, J.Leuthold, A.D.Ellis, I.Tomkos, *IEEE Journal of Selected Topics in Quantum Electronics* 18(2012)689.

[12] M. Vasilyev, T.I.Lakoba, *OpticsLetters* 30(2005)1458

[13] J.Wang, J.Yu, T.Meng ,W.Miao, B.Sun,W.Wang, E.Yang, *IEEE Photonics Journal* 4(2012)1816.

[14] N.M. Shah, M.Matsumoto, *IEEE Photonics Technology Letters* 22(2010)27

[15] N.S. MohdShah, M.Matsumoto, *Optics Communications* 284(2011)4687.

[16] S. Sun, S.Cui, J.Li, X.Fang, C.Ke,D.Liu, *Optics Communications(2012).*

[17] A.Bogris, D.Syvridis, *Journal of Lightwave Technology* 21(2003)1892

[18] E. Ciaramella, S.Trillo, *IEEE Photonics Technology Letters* 12(2000)849

[19] H. Zhou, K.Qiu, F.Tian, *Chinese Optics Letters* 10(2012)050601.

[20] I. Monfils, C.Ito, J.C.Cartledge, Optical 3R regeneration using a clock-modulated pump and higher-order four-wave mixing, *OFC2006, IEEE 2006*.

[21] Peter Andrekson, Fiber-optic Parametric Amplifiers and their Applications, By Department of Microtechnology and Nanoscience Chalmers University of Technology

[22] M. Westlund et al, El. Lett. 38, p. 85 (2002)

[23] R. Jiang et al, *IEEE Photon Technology Letters*, 18, p. 2445 (2006)

[24] N. Alic et al, *IEEE J. Sel. Top. in Q.E*,14, p. 681 (2008)

[25] T. Torounidis et al, *IEEE Photon Technology Letter* 19, p.1650 (2007)

[26] J. Hansryd et al, *Electron Letter*, 37, p. 584 (2001).

[27] M. Matsumoto,“Efficient all-optical 2R regeneration using self-phase

modulation in bidirectional BER configuration," *Opt. Express*, vol. 14, no. 23, 2006.

[28] Farag Z. El-Halafawy, Moustafa H. Aly, Maha A. Abd El-Baryl “Four-Wave Mixing Crosstalk in DWDM Optical Fiber Systems” by Faculty of Electronic Engineering, University of Menoufia, Menouf, Egypt

[29] N. S. Mohd Shah by All-optical regeneration based on four-wave mixing (FWM) in a highly nonlinear BER (HLNF) for time-interleaved multi-channel and multi-format signals.

[30] M. Vasilyev and T. I. Lakoba, All-optical multichannel 2R regeneration in a Fiber-based device," *Opt. Lett.*, vol. 30, 2005, pp. 1458-1460

[31] Ch. Kouloumentas, P.Vorreau, L. Provost, P. Petropoulos, W. Freude, J.Leuthold, and I.Tomkos, All-berized dispersion-managed multichannel regeneration at 43 Gb/s," *IEEE Photon. Technology Letters.*, vol. 20, 2008

[32] A. Cheng, C. Shu, and M.P. Fok, “All-Optical multi-wavelength extinction ratio enhancement via pump-modulated four-wave mixing,’’ *Proc. OFC*, 2009, paper JTh61

[33] N. S. Mohd Shah and M. Matsumoto, Analysis and experiment of all-optical time-interleaved multi-channel regeneration based on higher-order four-wave mixing in a fibre," *Opt. Comm.*, vol. 284, no. 19, 2011, pp. 4687-4694.

[34]] J. L. Blows, *Opt. Comm*., 236 (2004), 115.

[35] S.Watanabe ,T.Chikama, "Cancellation of Four wave mixing in multi channel fiber transmission by midway optical phase conjucation", *Electron letter*.30(14)1994.

[36] A.V.Ramprasad, M.Meenakshi, G.Geetha, R.Satheesh kumar, “Suppression of Four Wave Mixing Crosstalk Components in DWDM Optical Systems” by College of Engineering Anna university , Guindy Chennai, INDIA.

[37] K.Inoue, “Suppression Technique for Fibre Four Wave Mixing Using Optical Multi, Demultiplexer and a Delay Line” *Journal of lightwave technology* .Vol 11, NO3, March 1993.

[38] Xing- YuZhou, Bao-Jian Wun , Feng Wen, Hao Yuan, Kunqiu, “Investigation of crosstalk suppression technique for multi wavelength regeneration based on data pump FWM” by university of Electronic Science and Technology of China, Chengdu, China.

[39] O. Leclerc, B. Lavigne, D. Chiaroni, and E. Desurvire, “All-optical regeneration principles and WDM implementation,” *Optical Fiber Telecommunications IVA*,I. P. Kaminow and T. Li, Eds., Academic Press, San Diego, 2002

[40] H. Simos, A. Bogris, and D. Syvridis, \Investigation of a 2R all-optical regenerator based on four-wave mixing in a semiconductor optical amplifier," *J. Light wave Technology* Letter, vol. 22, no. 2, 2004.